Ductility and Energy Absorbing Behaviour of Coal Wash – Rubber Crumb Mixtures

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Abstract: The reuse of waste materials such as coal wash (CW) and rubber crumbs (RC) is becoming increasingly popular in large-scale civil engineering applications, which is environmentally friendly and economically attractive. In this study, the ductility and strain energy density of CW-RC mixtures with different RC contents compacted to the same initial void ratio and subjected to triaxial shearing are evaluated. As expected, the ductility and energy absorbing capacity of the waste mixture are improved with RC addition. This makes the use of CW-RC mixtures in substructure applications is a promising development for future rail design where loads are expected to increase. Furthermore, empirical models for the shear strength and strain energy density based on the RC content are proposed. These models may be used as a guide to approximate the shear strength and strain energy density of these compacted CW-RC mixtures prior to the undertaking of extensive triaxial tests.

Keywords: Coal wash; Rubber Crumbs; Ductility; Energy absorbing capacity

1. Introduction

Coal wash (CW) is a waste by-product of the coal washing process in mining operations, with several million tons produced each year in Australia [1]. On the other hand, approximately 50 million equivalent passenger units (EPU) of rubber tyres (1 EPU corresponds to a standard 8 kg rubber tyre) reach their end of life in Australia, equating to about two tyres per capita [2]. These waste materials are becoming an increasing problem within many developed and industrial countries as they are generally disposed of in landfills or stockpiled, leading to the occupation of usable land [3]. Non-recycled scrap tyres can lead to various economical, health and environmental concerns, and fires in stockpiles of waste tyres can occur due to exothermic reactions of rubber leading to spontaneous combustion and the release of toxic gases [4–6]. Moreover, measures have also been put in place with a levy of AUD $15.00 per tonne of coal washery rejects received from off-site and applied to land as an economic incentive to develop alternatives to disposal in Australia [7]. Therefore, it is of great significance to reuse these waste products in large-scale civil engineering projects as large quantities can be removed/diverted from stockpiles and landfills, thus reducing the negative health and environmental impacts as well as the requirement for valuable natural aggregates to be obtained through quarrying [8,9]. The use of scrap tyres in civil (geotechnical) engineering applications has been standardised by ASTM [10], where specifications on aspects such as sizing, material properties, and construction practices are provided.

For important structures, a prolonged ductile failure is preferred over a sudden and brittle one. Railway tracks are no different in this regard as a brittle failure of the substructure can be catastrophic due to the high train speeds and civilian use. As an individual material, compacted coal wash has a brittle strain-softening response similar to a dense sand at relatively low confining pressures ($\sigma'_3 \leq 50$ kPa) [11]. As a result, it is unlikely to be suitable for substructure use in this aspect. Although, rubber has been shown to increase the ductility and reduce the stiffness of sand [6,12–15], rubberised concrete [16–19], and other waste material mixtures [9,20–23], in the long term, the stiffness of the mixture can increase due to creep deformation, especially when the host materials are crushable like coal wash [24]. Therefore, the addition of rubber crumbs (RC), produced by shredding scrap tyres, may enhance the ductile capacity of CW and render it suitable for track substructure use.

The energy absorbing capacity and damping properties of rubber are also ideal for dynamic applications. Its use in soil mixtures [9,20,22,25,26], and under sleeper pads [27] has been shown to improve energy dissipation, decrease particle breakage, and reduce vibration intensity. Enhancing the energy absorption of the subballast layer may help reduce the energy transferred to the underlying subgrade. This is important as most coastal regions in Australia have very soft clays with a low bearing capacity and high compressibility [28] and hence strength and excessive settlements are a major concern for track design. Furthermore, a compressible and energy absorbing subballast layer can act as a flexible cushion, helping to reduce breakage of the overlying ballast layer as well. Overlying a stiffer substructure, ballast subjected to impact loading experienced more breakage compared to that on top of a more compressible layer [28]. An increased number of fines from this breakage process can lead to fouling and reduce the stiffness of the ballast layer, causing potential track instability and degradation. Therefore, the higher ductility and energy absorbing potential of these recycled waste materials may help reduce track degradation over time and lead to an overall safer design.

This study aims to investigate the influence rubber crumb content has on the ductility, shear strength and strain energy absorption of a compacted CW-RC matrix. Furthermore, by comparing the geotechnical properties of the mixtures to that of typical subballast materials, an optimal RC content is proposed. To achieve this, the consolidated drained monotonic triaxial tests results on CW-RC mixtures with varying RC contents (0, 5, 10, and 15% by weight) tested by Indraratna et al. [20] were adopted in this study. The test specimen was compacted at a modified energy level in order to reach an initial void ratio of 0.3 suggested by Australian Rail Track Corporation [29]. The tests were conducted at a range of relatively low effective confining pressures (σ'_3 = 10, 25, 50, and 75 kPa) to simulate the low magnitude of confinement in typical subballast conditions. The particle size distribution of the CW-RC mixtures is provided in Figure 1. For detailed specimen preparation and test procedures, see [9,20].

2. Ductility of the waste material matrix

The stress-strain curves for the CW-RC mixtures tested at $\sigma'_3 =$ 10, 25, 50, and 75 kPa are shown in Figure 2. It is to be noted that no tests have been undertaken for 15% RC at 10 kPa confining pressure. It can be seen that the peak deviator stress, q_{peak}, decreases and the corresponding axial strain (ε_1) at q_{peak} increases with RC contents. This can be attributed to the lower shear strength and higher compressibility of RC with increased rubber-to-rubber interactions within the skeleton as RC contents increase [6,22]. Additionally, the curvature of the stress-strain response at the peak becomes broader with RC addition. In other words, the addition of RC has caused a transition from a predominately brittle to a more ductile post-peak state for the waste mixture. This transition is especially important for railway applications as large loads and high speeds coupled with sudden failure of the track can cause catastrophic train derailments. The increased ductility means that, although larger settlements are experienced, the substructure can sustain a larger post-peak load and lower the potential risk of financial and human loss from derailments.

Moreover, all the test specimens achieved the residual state by the end of the test ($\varepsilon_1 = 20\%$), where the reduction of deviator stress is negligible upon further straining in the vertical direction. Note that, under a certain σ'_3 all the CW-RC mixtures tend to end up with similar residual state deviator stress ($q_{residual}$), indicating the addition of RC does not incur a significant impact on the residual strength of the waste mixture.

The volume change behaviour for each mixture is also contained in Figure 3. All specimens exhibited an initial volumetric contraction, with the compressive peak occurring at a larger axial strain as the rubber content within the mixture increases. Before the addition of rubber, due to the incompressibility of the CW particles, the optimum packing arrangement of the skeleton (by particle breakage and rearrangement mostly) is reached at a much earlier stage of loading and strain. As RC is added and compressed, further voids/spaces are created for the CW particles to occupy and the optimum packing arrangement is reached at a later stage. Additionally, at a confining pressure of 50 kPa, the mixtures with at least 10% RC remained contractive at failure.

To evaluate the ductility of the CW-RC mixture, the brittleness index (I_B) initially proposed by Consoli et al. [30] is adopted in this study, which is defined as

$$I_B = \frac{q_{peak}}{q_{residual}} - 1 \tag{1}$$

where q_{peak} and $q_{residual}$ are the peak and residual state deviator stresses, respectively. The smaller the value of the brittleness index, the greater the ductility of the material.

The brittleness indices of the CW-RC mixtures with respect to the RC content and confining pressure are shown in Figure 4. Generally, I_B decreases with the increasing RC content when RC $\leq 10\%$, then it increases again as 5% more RC is added. This indicates that the mixture has the minimum brittle index (i.e., the maximum ductility) when adding 10% RC (Figure 4 (a)). This is because when the mixture skeleton is formed by CW (RC$\leq$

10%), The brittleness is positively correlated to the particle breakage of the materials (i.e. coal wash in this study) as particle breakage cause the material skeleton to lose its original structure and deteriorate its stress bearing capacity [31]. By adding rubber, particle breakage of the CW-RC mixture was reduced significantly (e.g. 18% and 46% reduction by adding 0% and 10% rubber, respectively) reported by Qi et al. [32], which would have certainly contributed to the reduction of the brittleness as rubber content increases. However, when RC>10%, the skeleton of the CW-RC mixtures is pronouncedly influenced by rubber particles, thus the reduction of particle breakage becomes insignificant by adding more rubber (only 1% more by increasing rubber content from 10% to 15% [32]). Therefore, no further reduction in brittleness can occur by adding more rubber. For a CW-RC mixture with a certain RC content, I_B decreases as the effective confining pressure increases, albeit fluctuation is observed for the mixture with 5% RC (Figure 4 (b)). Additionally, when compared to typical subballast, all CW-RC mixtures are more ductile at lower confining pressures ($\sigma'_3 \leq 25$ kPa). Mixtures with 10% and 15% RC are the best performing with lower I_B indices than the subballast under all confining pressures tested.

3. Shear Resistance

3.1. *Internal friction angle*

Several studies on rubber-soil and rubber-waste mixtures [6,9,20,22] have analysed the peak friction angle with respect to the rubber content. This parameter is indicative of the shear strength at a certain confining pressure since it is a function of σ'_3 and is therefore an extrinsic material property. The use of a constant and intrinsic friction angle, ϕ', may be more beneficial and efficient for use in geotechnical design. Table 1 shows the peak friction angle and internal frictional angle of the CW-RC mixtures.

Figure 5 compares the internal friction angle for the CW-RC mixtures (obtained using Mohr circles and linear failure envelope for peak stress values) with $\phi' = 41.6°$ for typical subballast determined from tests conducted by Qi et al. [22]. It is noteworthy that when the amount of rubber is more than 10%, the internal friction angle becomes less than that of traditional subballast, suggesting the CW-RC mixtures should keep the rubber content $\leq$ 10% to ensure a superior shear strength in contrast to conventional subballast. The Mohr circles and approximated linear failure envelope for the mixture with 10% RC are contained in Figure 6. It should be stressed that this angle of friction can be simplified as a constant to fit a linear failure envelope, while for these types of waste materials it is likely to be non-linear with the variation of σ'_3 [20,22,33]. Non-linear failure envelopes are also observed for CW [34] and sand-rubber mixtures [6,12]. Under lower confining pressures, and hence normal stresses, the discrepancy between these linear and non-linear models becomes more noticeable and as such a relatively high cohesion intercept obtained from a linear model may be misconstrued. A linear Mohr Coulomb frictional model is better representative of loose soils with loosely packed particle arrangements. As the rubber content increases so too does the degree of particle packing within the matrix to comply with the compaction requirements suggested by Australian Rail Track Corporation [29]. Accordingly, mixtures with higher rubber contents conform less to a linear failure envelope, especially at lower confining pressures where the influence of additional particle interlocking resistance is more significant relative to the confinement provided.

Furthermore, as the normal stress increases so too does the particle breakage due to concentrated stress points between particles within a granular matrix. This reduces the interlocking forces and hence the envelope diverges from the linear Mohr-Coulomb model for these higher stresses as well. This is supported by experimental studies on CW

[3,34,35,36] where non-linear envelopes are also observed as it is more susceptible to higher breakage relative to other rigid aggregates, particularly under higher normal stresses [3,9,11,22,36,37]. Although, as rubber reduces particle breakage due to its energy absorbing properties, the divergence from a linear envelope is relatively small within the range of confining pressures tested (Figure 6).

3.2. *Shear Strength Model*

The shear strength, τ_f, is obtained corresponding to the peak deviator stress suggested by Qi et al. [22] for SFS-CW-RC mixtures and Kim and Santamarina [15] for sand-rubber mixtures as in Equation (2a):

$$\tau_f = \frac{q_{peak} \cos \phi'_{peak}}{2} \tag{2a}$$

Both linear and non-linear failure envelopes for the CW-RC mixtures with 10% RC are constructed from the Mohr circles in Figure 6. Although the envelopes are similar for the range of stresses tested, a linear envelope with a non-zero cohesion intercept may overestimate the shear strength of the mixtures, particularly at lower confining pressures. Additionally, as previously discussed, CW exhibits non-linear shear behaviour, particularly at higher stresses due to the impact of particle breakage and a linear model is therefore likely to overestimate the shear strength at higher confining pressures as well.

A non-linear failure envelope in the form of a power function (Equation 2b) is proposed to better describe the cohesionless shear strength of these granular CW-RC mixtures:

$$\tau_f = \alpha {\sigma_n}^{\beta} \tag{2b}$$

where σ_n is the normal stress at failure; and α and β are functions of rubber content

(Equations 2c,d):

$$\alpha = a_1 e^{-a_2 X_{RC}} \quad (2c)$$

$$\beta = a_3 X_{RC} + a_4 \quad (2d)$$

where a_1, a_2, a_3, and a_4 are calibration parameters (Table 2) and X_{RC} is the percentage of rubber within the total mixture, defined by Equation (2e):

$$X_{RC} = \frac{Mass\ of\ RC}{Total\ Mass\ of\ CW{-}RC\ Mixture} \times 100\% \quad (2e)$$

Therefore, mixtures with RC:CW ratios of 5%, 10%, and 15% correspond to respective X_{RC} values of 4.76, 9.09, and 13.04. Figure 7 compares the calculated shear strength from this model against the measured values, as well as those from numerous studies on other granular mixtures containing rubber, which shows a coefficient of determination of, R^2 $a$pproaching 0.95. When extended to pure rubber (i.e. $X_{RC} = 100$), the proposed model underestimates the shear strength obtained from previous studies [12,13,38], especially at lower normal stresses. This discrepancy may be attributed to the following factors:

Particle breakage: The model may not adequately encapsulate the effect CW breakage has on the shear strength of the mixture. Equation (2b) does not possess a term directly related to breakage, although it is indirectly dealt with as a result of the shear and normal stress data used in the calibration of the model. Therefore, the model may still indirectly account for CW breakage even for pure rubber and hence underestimate the shear strength as rubber would not experience breakage under these stresses due to its high compressibility and energy absorbing capacity. The investigation of a parameter incorporating particle breakage is therefore suggested to further calibrate the shear strength model for use with higher rubber contents.

Cohesion of rubber: Several studies [12,13,39] have reported non-zero cohesion values for rubber which is an apparent cohesive-frictional material as different to traditionally cohesionless granular materials. At low rubber contents the influence of this inclusion is estimated to be relatively low with respect to the large portion of coal wash within the matrix. This is in line with previous studies e.g. [40–42] which also suggested to take the aggregate-rubber mixtures as purely frictional materials in terms of physical mechanism contributing to strength. However, at higher rubber contents this influence may become more significant and therefore, as the model is calibrated based on a cohesionless mixture, the shear strength may be underestimated. Therefore, in order to be applied to an extended range of rubber contents (including pure rubber), a parameter relating cohesion and rubber content may need to be introduced to the model. This is a limitation of the proposed model and requires further investigation so that the model's accuracy is improved for mixtures with greater rubber contents.

Furthermore, this model is developed based on low rubber contents and it may therefore inaccurately predict the shear behaviour at higher RC contents where the mixture transitions to a predominately rubber-like behaviour. Consequently, a limiting rubber content of RC $<$ 60% by volume is proposed as rubber-to-rubber interfaces remain absent within the skeleton [15,21,43]. Equation (3) can be used to convert the volumetric content of rubber within the mixture to the weight content:

$$X_{RC} = \frac{\chi_{RC}\left(\frac{G_{s,RC}}{G_{s,CW}}\right)}{\frac{\chi_{RC}}{100}\left(\frac{G_{s,RC}}{G_{s,CW}}-1\right)+1} \tag{3}$$

where χ_{RC} is the percentage of RC within the total mixture by volume, and $G_{s,RC}$ and $G_{s,CW}$ are the specific gravities of the rubber crumbs and coal wash, respectively. The derivation of Equation (3) is contained in the Appendix. A volumetric content of 60% RC corresponds to around 40% RC by weight for these CW-RC mixtures and hence a limiting rubber content of $X_{RC} < 40\%$ should be placed on the proposed shear strength model.

In view of the above, the proposed model is currently appropriate for use with the compacted CW-RC mixtures investigated in this study. For use with other waste rubber mixtures, the proposed model will require recalibration to better represent their specific shear strength response. This requirement is illustrated in Figure 7 where the model generally underestimates the strength of both SFS-CW-RC [22] and sand-tyre crumb mixtures [6]. This may be attributed to the lower particle breakage potential of these mixtures compared to CW-RC mixtures – this reasoning is discussed previously with respect to the model underestimating the strength for pure rubber.

4. Energy Absorption Characteristics

4.1. *Strain Energy Density*

The strain energy density, E, can be used to assess the strain energy absorption under triaxial shearing. It is defined as the total area under the shear stress-strain curve up to failure (Equation (4) and Figure 8 (b)).

$$E = \int_0^{\gamma_f} \tau_f d\gamma \quad (4)$$

where E is the strain energy density (kPa), τ_f is the shear strength (kPa), and γ and γ_f are the shear strain and shear strain at failure (dimensionless), respectively.

Figure 8 (a) presents the strain energy density of the CW-RC mixture with varying RC contents. As expected, E increases with rubber contents except for 15% RC at $\sigma'_3 = 25$ kPa. Qi et al. [22] also observed a similar response for SFS-CW-RC mixtures (mixtures of steel furnace slag (SFS), CW and RC). Noted that the most significant increase is observed for the initial addition of rubber, after which the increasing rate decreases. This is most likely due to the reduction in shear strength. Referring to Figure 8 (b), the pure CW has a lower strain energy density compared to that of typical subballast material and SFS-CW blends under monotonic triaxial tests conducted by Qi et al. [22]. As the confining pressure increases so too does the divergence of the CW from other materials (i.e. subballast, CW-RC, and SFS-CW mixtures) which is likely attributed to the significantly higher susceptibility to particle breakage CW possesses. As reported by Indraratna et al. [20], pure CW had 13% and 46% more breakage than CW-RC mixtures with 5% RC and 15%, respectively. As breakage continues under shearing, the friction and interlocking resistance between particles may reduce and, as there is less particle movement, the CW experiences shear failure at a lower strain compared to other materials that experience less breakage. In other words, there is less time taken for the CW skeleton to reach its optimum particle arrangement which can result in a more abrupt failure and a stress-strain curve with less curvature compared to other materials that experience less breakage.

The results in Figure 8 (b) further highlights the influence that even a small amount of rubber crumb addition has on the energy absorbing capacity of these waste mixtures. Although pure CW has a much lower strain energy density (as low as 43% relative to typical subballast), there is a significant increase with the initial addition of 5% RC such that the CW-RC mixture is comparable to other materials without rubber (i.e., SFS-CW mixture and typical subballast) at low confining pressures ($\sigma'_3 \leq 25$ kPa). Although, at these low confining pressures the increase in E between the mixtures having differing RC contents is marginal. This trend was also observed with SFS-CW-RC mixtures by Qi et al. [22]. Typical railway conditions in Australia have confining pressures within this relatively low range and therefore the preferable RC content for CW-

RC mixtures, whether it be 5 or 15%, makes little difference for enhancing the material's strain energy absorbing potential for smaller axle loads.

Future developments within the industry may require trains to travel at higher speeds with heavier axle loads, meaning the applied pressures on the track will need to be increased if this is the case [44]. Therefore, increased layer thicknesses or other methods may need to be employed in order to increase the confining pressure on the substructure [45,45]. However, under larger confining pressures, these mixtures do not perform as well. At $\sigma'_3 = 50$ kPa, only a rubber content of 15% observes an increase in strain energy density relative to typical subballast, with 10% RC resulting in a value around the same. So, it seems that the CW-RC mixtures are more appropriate for these typically lower confining pressures with respect to an increase in energy absorption relative to typical subballast material. This may be attributed to the increase in particle breakage of CW under larger confining pressures. The strain energy density of the individual CW material is significantly lower than that of subballast for these larger confining pressures ($\sigma'_3 \geq 50$ kPa). This is illustrated in Figure 8 where subballast has a relatively constant increase in E with respect to confining pressure whereas CW experiences a diminishing increase and plateaus out. Although, typical stress ratios of σ'_1/σ'_3 between 3 and 4 are experienced at the subballast layer [47], corresponding to a ratio of q/σ'_3 between 2 and 3. Figure 9 shows a similar trend with a clear improvement in strain energy density (calculated up to $q = 2\sigma'_3$) for the higher confining pressures. The data shows that the role of RC is more prominent at larger loads, thus having an optimal RC of 10% will be of practical relevance for heavy haul tracks.

Moreover, typical track loading in the field is dynamic and cyclic in nature unlike the static loading conditions for the monotonic triaxial tests which this study is based on. Furthermore, the track is typically granted a rest period between loading cycles – i.e., the time between successive trains passing over the same track section. Under static loading, the rubber particles are unable to recover the elastic portion of their deformation due to the constant and increasing nature of loading. For example, Tawk et al. [48] observed a greater energy absorption of CW-RC mixtures under cyclic loading when a rest period was introduced. As a result, the energy absorbing capabilities of these waste mixtures cannot be fully extrapolated in the context of rail applications. Nevertheless, the improved strain energy absorption (and REAP discussed in the following section) with rubber crumb content due to its elasticity and ductility is clearly evident.

4.2. *Representative Energy Absorbing Parameter*

The representative energy absorbing parameter, or REAP, is a dimensionless index introduced herein as the ratio of the strain energy density of the CW-RC mixture (E_{CW-RC}) to the pure CW (E_{CW}):

$$REAP = \frac{E_{CW-RC}}{E_{CW}} \tag{5}$$

In other words, it is a measure of the increase in strain energy density normalised to the material without rubber. Figure 10 illustrates the REAP values obtained from the triaxial testing. It is interesting to note that the tests at $\sigma'_3 = 10$ kPa yielded the highest REAP values, a trend also observed for SFS-CW-RC mixtures as reported by Qi et al. [22]. This is likely a result of the steep shear stress-strain curve and smaller shear strain at failure for 100% CW at $\sigma'_3 = 10$ kPa, hence a relatively low value of E_{CW}.

Referring to earlier Figure 5 where a RC content of up to 10% possessed a friction angle exceeding that of typical subballast, this corresponds to a REAP of 1.79 at a confining pressure of 25 kPa. In other words, the CW-RC mixtures can have an increase in strain energy density of 79% relative to the pure CW material under typical subballast confinement conditions until the friction angle becomes inadequate. When normalised to the strain energy density of typical subballast material, this increase is 43% under the same confining pressure of 25 kPa.

4.3. *Empirical Relationship for Strain Energy Density*

From Figure 11 (a), a quasilinear trend between the strain energy density and shear strength is observed in the form of Equation (6a):

$$E = \psi \tau_f \tag{6a}$$

where ψ is an empirical parameter to account for the curvature of the stress-strain response, and is a function of rubber content, depicted in Figure 11 (b) and Equation (6b):

$$\psi = a_5 X_{RC} + a_6 \tag{6b}$$

where a_5 and a_6 are calibration parameters (Table 2). Although Equation (6a) appears to be linear, it is a function of the shear strength and hence, through Equation (2b), the strain energy density possesses a non-linear relationship with rubber content. This is an expected result and is consolidated by Figure 8 (b) where the most significant increase in E is observed for the initial addition of rubber, after which the relative increase diminishes with further rubber addition. A comparison between the strain energy density calculated by Equation (6a), additionally incorporating the shear strength model from Equation (2b), and the measured values are presented in Figure 12 where a good agreement can be observed ($R^2 = 0.98$). The strain energy density model is tested against an external dataset with SFS-CW-RC [22] for validation purposes (Figure 13). The model achieved a reasonable level of accuracy ($R^2 = 0.86$), although different values for a_5 and a_6 are better suited for these different mixtures due to their differing stress-strain response.

Therefore, for use with other mixtures containing waste rubber inclusion, the parameters in this model should be recalibrated to better represent the specific mixture. Additionally, further investigation on the validity of this model for mixtures with higher rubber contents is required and therefore should be limited to 15% by weight at present.

5. Conclusions

In this study, rubber crumbs were blended with coal wash and compacted to the same initial void ratio. Triaxial tests conducted on four different CW-RC mixtures under different effective pressures were examined in terms of their ductility, shear resistance, and strain energy absorption. The following conclusions can be drawn:

(1) As RC contents increased, the mixtures reduced in stiffness and transitioned from a predominantly brittle to a more ductile post-peak state, with the most significant decrease occurring for the initial addition of rubber. Although the peak strength reduced with rubber content, the residual strength remained fairly consistent between the various mixtures, with a range of 44 – 50 kPa and 69 – 89 kPa for $\sigma'_3 = 10$ kPa and 25 kPa, respectively.

(2) The brittleness index was used as a measure to evaluate ductility and was at a minimum for the mixtures containing 10% RC at all four confining pressures tested, with the lowest value being $I_B = 0.62$ at $\sigma'_3 = 50$ kPa. At confining pressures ≤ 25 kPa, all CW-RC mixtures possess a lower brittleness index when compared to typical subballast aggregates. Similarly, mixtures with 10% and 15% rubber crumb content outperform the typical subballast with respect to I_B for all confining pressures tested.

(3) The most significant increase in strain energy density was observed for the initial inclusion of rubber, with an increase of up to 100% (i.e., doubled) at $\sigma'_3 = 10$ kPa when compared to the pure CW material. Further improvements at higher RC contents were less significant at low confining pressures (≤ 25 kPa). When evaluated at typical stress ratios experienced at the subballast layer, the strain energy density of the mixtures with 10% RC improved by 122–171% compared to the pure CW material.

(4) The internal friction angle of the mixtures was greater than that of typical subballast (41.6°) for RC contents up to 10%, allowing for a 79% and 43% increase in strain energy density relative to the pure CW and typical subballast material, respectively, under typical Australian track conditions.

(5) Empirical models developed to estimate the shear strength and strain energy density of the waste mixtures based on rubber content were in good agreement with the experimental results within this study. The shear strength model generally underestimated the measured values with an R^2 value of 0.94 and is therefore more suited for use as a lower bound validation. However, the model grossly underestimated the shear strength of pure rubber and therefore a limiting RC content of 40%, corresponding to the point where the material transitions to a rubber-like behaviour, is suggested. Furthermore, as these are only empirical and rely on several empirical constants, further recalibration of these equations should be assessed when investigating other mixtures containing rubber crumbs.

(6) Overall, the inclusion of granulated rubber crumbs significantly improves the ductility and energy absorbing capabilities of coal wash, particularly for rubber contents up to 10% by weight. Although, under typical track conditions, loading is dynamic and cyclic in nature, with rest periods allowing for recovery of elastic

deformation. Therefore, the improved strain energy absorption of CW-RC mixtures in this study should only be used in support of studies incorporating cyclic loading to assess their suitability as an energy absorbing subballast layer.

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Notation

CW	coal wash
RC	rubber crumbs
REAP	representative energy absorbing parameter
SFS	steel furnace slag
E	strain energy density (kPa)
E_{CW}	strain energy density of pure coal wash (kPa)
$E_{\mathrm{CW\text{-}RC}}$	strain energy density of coal wash-rubber crumb mixtures (kPa)
$G_{s,CW}$	specific gravity of coal wash
$G_{s,RC}$	specific gravity of rubber crumbs
$G_{s,mix}$	specific gravity of mixture
M_{RC}	mass of rubber crumbs
M_{mix}	mass of mixture
ρ_{RC}	density of rubber crumbs
ρ_{mix}	density of mixture
q	deviator stress (kPa)
q_{peak}	peak deviator stress (kPa)
$q_{residual}$	residual deviator stress
V_{RC}	volume of rubber crumbs
V_{mix}	volume of mixture
X_{RC}	rubber crumb fraction of total waste mixture by weight (%)
χ_{RC}	rubber crumb fraction of total waste mixture by volume (%)
ε_1	axial strain (major principle strain) (%)
γ	shear strain (%)
γ_f	shear strain at failure (%)
σ'_1	major principle stress (kPa)

σ'_3	effective confining pressure (minor principle stress) (kPa)
τ	shear stress (kPa)
τ_f	shear strength (kPa)
ϕ'	internal friction angle (°)
ϕ'_{peak}	peak friction angle (°)

Data availability statement

The data that support the findings of this study are available from the corresponding author, [B.I.], upon reasonable request.

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Appendix

Derivation of volume fraction to mass fraction of rubber crumb content conversion

The mass fraction of RC within the total mixture, X_{RC}, is defined as:

$$X_{RC}\ (\%) = \frac{M_{RC}}{M_{mix}} \times 100 \tag{A1}$$

where M_{RC} and M_{mix} are the masses of the rubber crumbs and the total mixture, respectively.

Similarly, the volumetric fraction of RC within the total mixture, χ_{RC}, is defined as:

$$\chi_{RC}\ (\%) = \frac{V_{RC}}{V_{mix}} \times 100 \tag{A2}$$

where V_{RC} and V_{mix} are the volumes of the rubber crumbs and the total mixture, respectively.

By definition,

$$M_{RC} = V_{RC}\rho_{RC} \tag{A3}$$

$$M_{mix} = V_{mix}\rho_{mix} \tag{A4}$$

where ρ_{RC} and ρ_{mix} are the densities of the rubber crumbs and the mixture, respectively.

Therefore, Equation (A1) can be rewritten as:

$$X_{RC}\ (\%) = \frac{V_{RC}}{V_{mix}}\frac{\rho_{RC}}{\rho_{mix}} \times 100 \tag{A5}$$

From Equation (A2), Equation (A5) can be rewritten as:

$$X_{RC}\ (\%) = \chi_{RC}\frac{\rho_{RC}}{\rho_{mix}} \tag{A6}$$

However, the ratio of the densities may also be expressed as an equivalent ratio of the specific gravities:

$$\frac{\rho_{RC}}{\rho_{mix}} = \frac{G_{s,RC}}{G_{s,mix}} \tag{A7}$$

where $G_{s,RC}$ and $G_{s,mix}$ are the specific gravities of the rubber crumbs and mixture.

Adapted from Indraratna et al. [20], the specific gravity of the mixture may be expressed as:

$$G_{s,mix} = \frac{1}{\frac{X_{RC}}{G_{s,RC}} + \frac{100 - X_{RC}}{G_{s,CW}}} \tag{A8}$$

where $G_{s,CW}$ is the specific gravity of coal wash.

Therefore, the mass fraction of the rubber crumbs within the mixture may be calculated as:

$$X_{RC}\ (\%) = \frac{\chi_{RC}\left(\frac{G_{s,RC}}{G_{s,CW}}\right)}{\frac{\chi_{RC}}{100}\left(\frac{G_{s,RC}}{G_{s,CW}} - 1\right) + 1} \tag{A9}$$

Noted that a volumetric RC content of 60% corresponds to $\chi_{RC} = 60$ in the above equation.

Table 1. Shear strength and strain energy density of CW-RC mixtures from monotonic triaxial tests

σ'_3 (kPa)	RC:CW (%)	X_{RC} (%)	τ_f (kPa)	ϕ'_{peak} (°)	ϕ' (°)	E (kPa)
10	0	0	33.7	61.0	45.0	0.67
	5	4.76	28.6	57.2	44.3	1.34
	10	9.09	25.4	54.5	42.0	1.73
25	0	0	62.8	54.2	45.0	2.16
	5	4.76	57.3	52.0	44.3	3.28
	10	9.09	50.5	49.0	42.0	3.87
	15	13.04	45.5	46.5	40.6	3.83
50	0	0	107.4	50.5	45.0	2.91
	5	4.76	99.2	48.6	44.3	4.63
	10	9.09	92.7	47.0	42.0	5.67
	15	13.04	82.0	44.1	40.6	6.72
75	0	0	144.3	47.9	45.0	3.95
	5	4.76	143.2	47.7	44.3	6.33
	10	9.09	124.6	44.4	42.0	7.28
	15	13.04	120.9	43.6	40.6	8.62

Table 2. Calibration parameters for shear strength and strain energy density models

Source	Parameter	Value
Shear strength Eq. 2(c-d)	a_1	3.6986
	a_2	0.064
	a_3	0.0106
	a_4	0.7529
Strain energy density, Eq. 6b	a_5	0.0036
	a_6	0.0282

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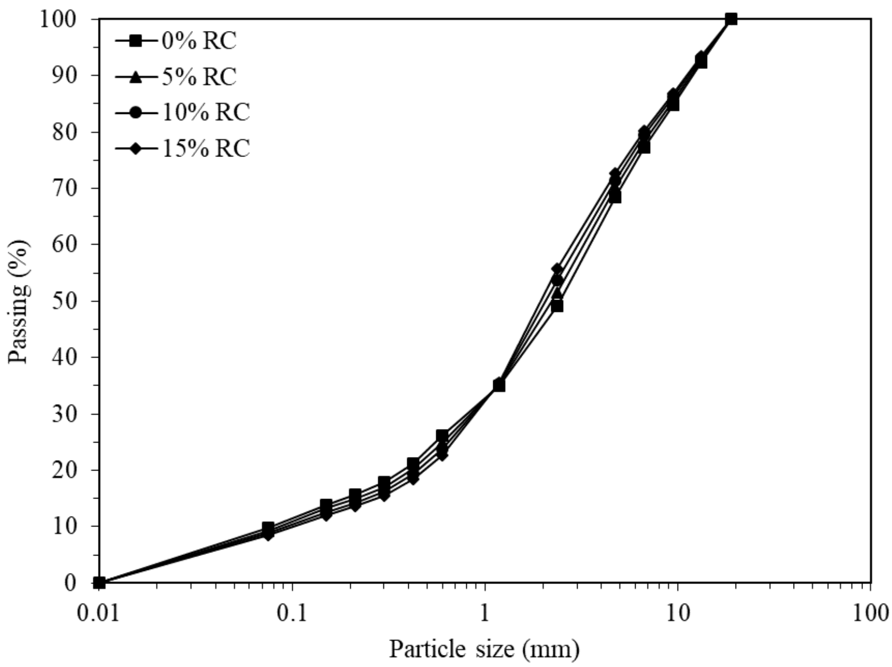


Figure 1. Particle size distribution of CW-RC mixtures with varying rubber content

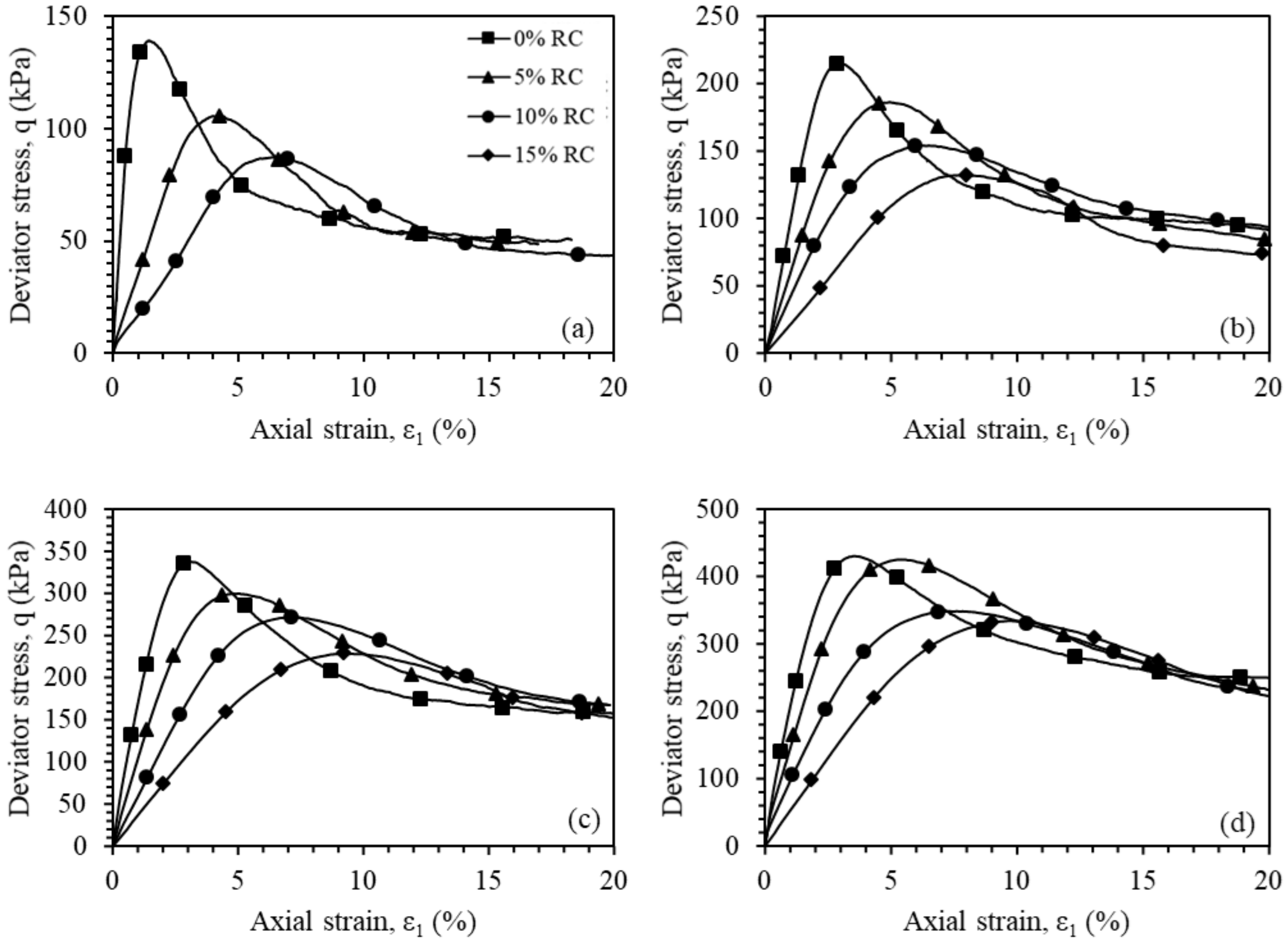


Figure 2. Stress-strain curves of CW-RC mixtures at effective confining pressures of (a) 10 kPa; (b) 25 kPa; (c) 50 kPa; (d) 75 kPa (Modified after Indraratna et al. [20])

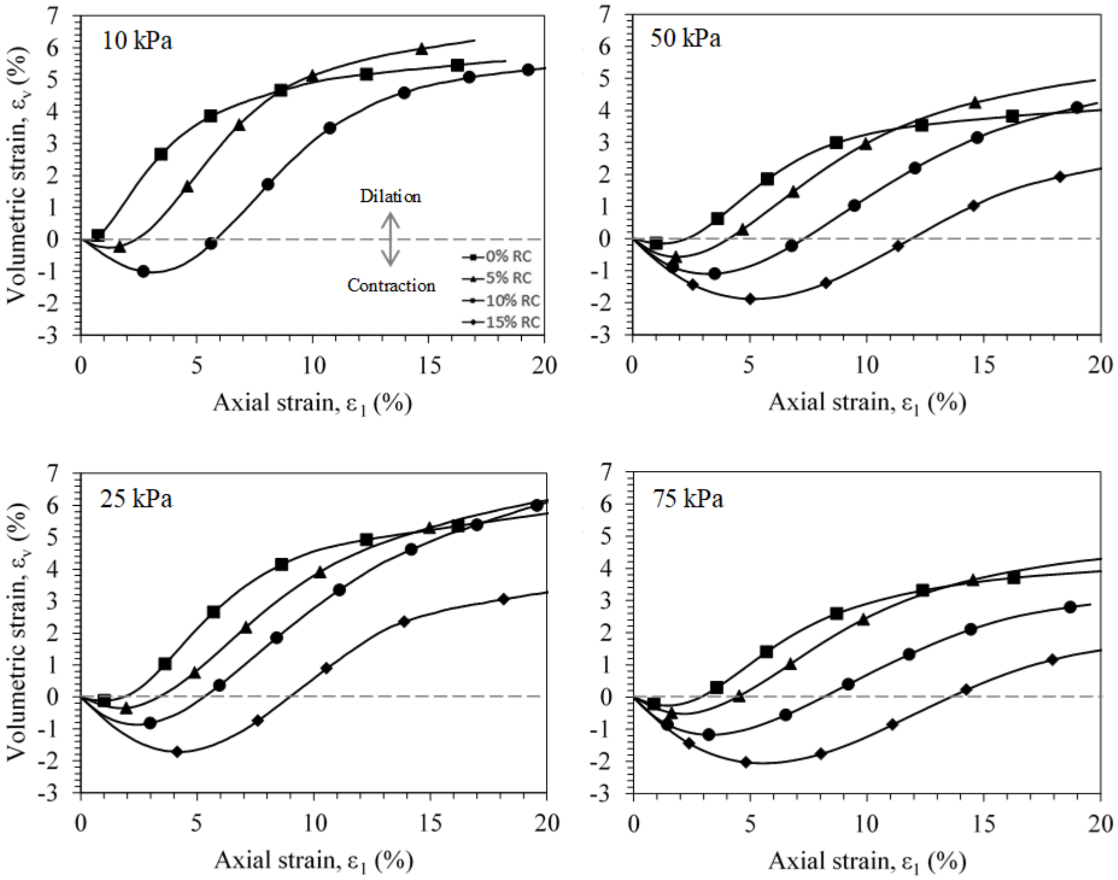


Figure 3. Volume change behaviour of CW-RC mixtures with varying rubber content and effective confining pressures (Modified after Indraratna et al. [20])

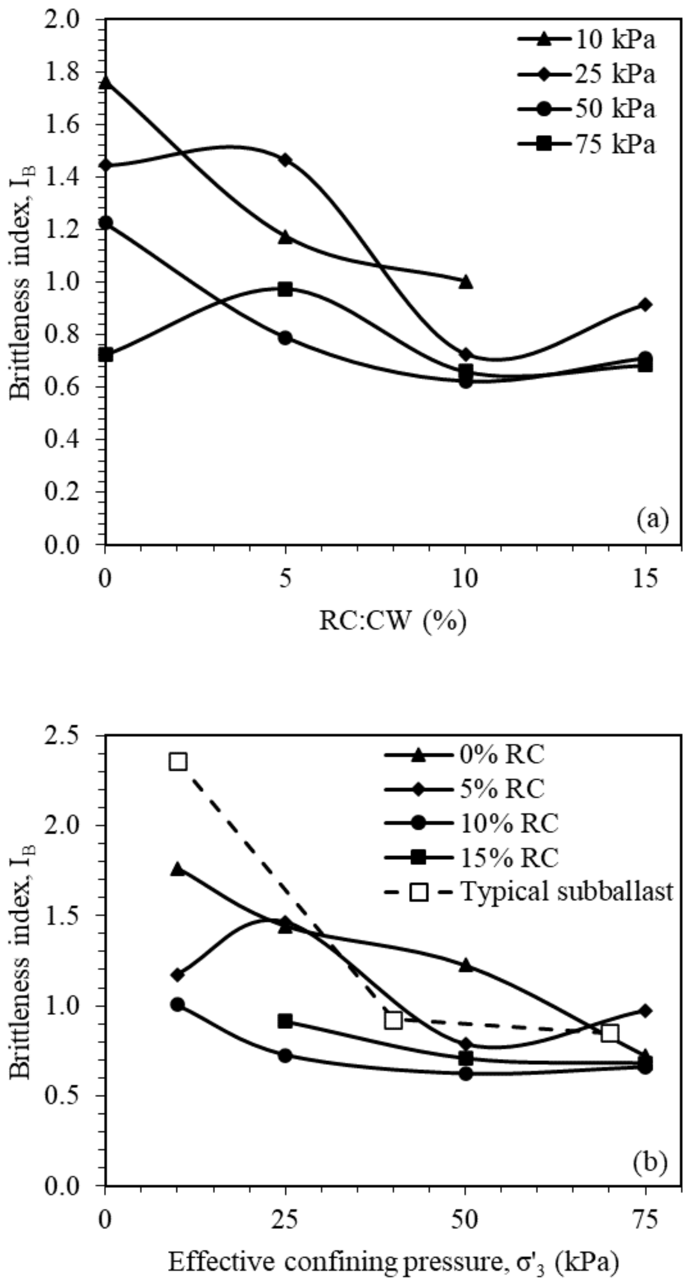
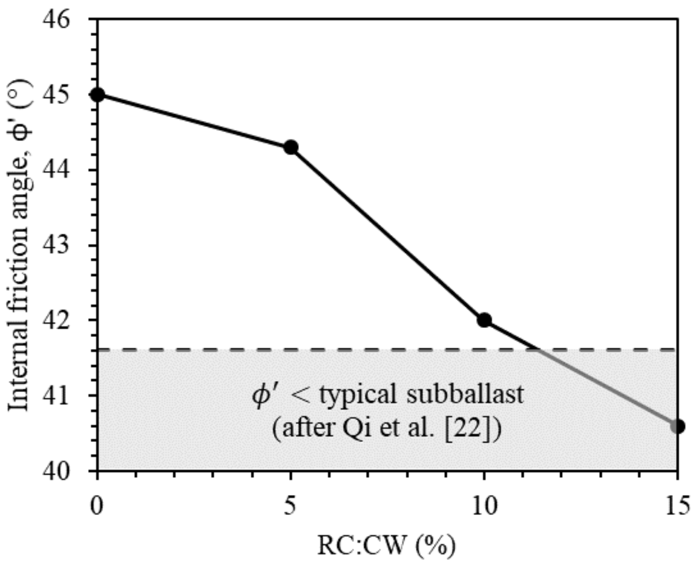


Figure 4. Brittleness index of CW-RC mixtures with respect to (a) RC content and (b) confining pressure compared to typical subballast



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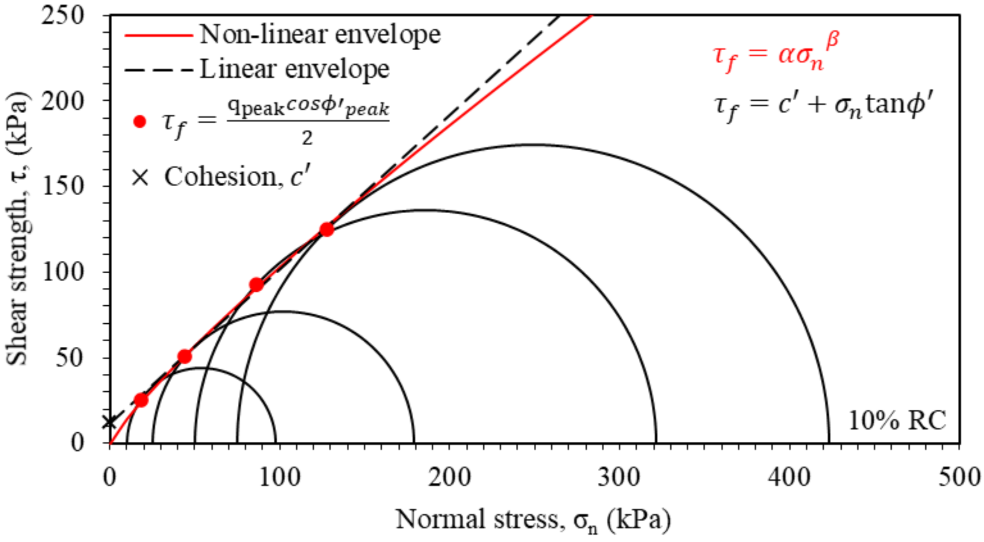

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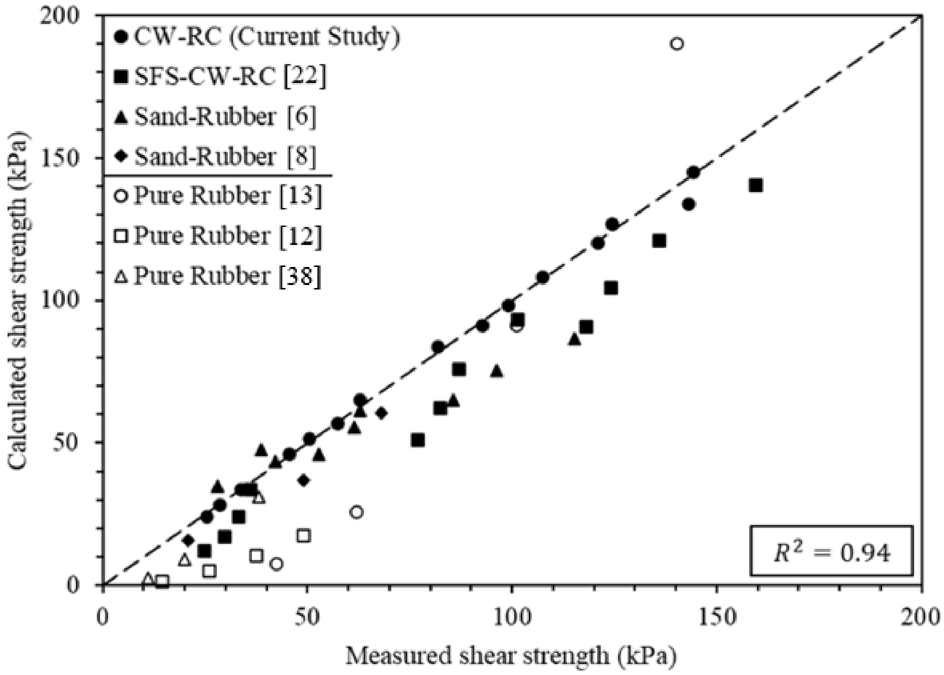

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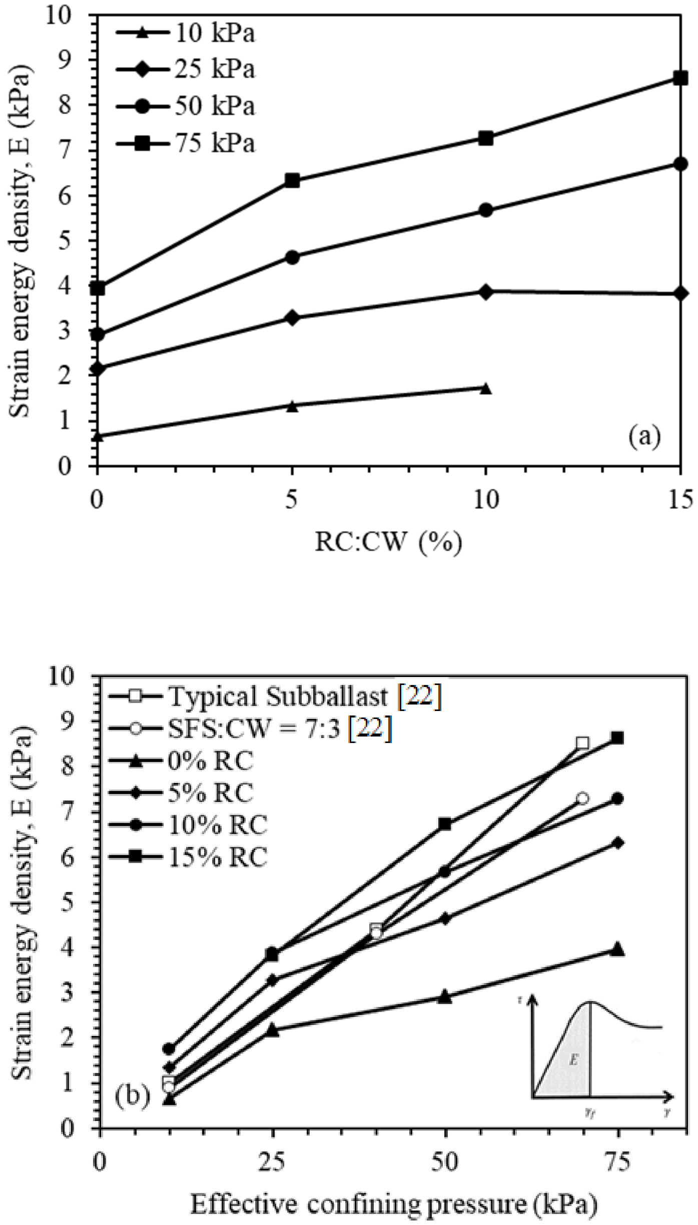


Figure 8. Strain energy density of CW-RC mixtures (a) under varying confining pressure; and (b) in comparison to typical subballast and steel furnace slag-coal wash waste mixture with definition of strain energy density

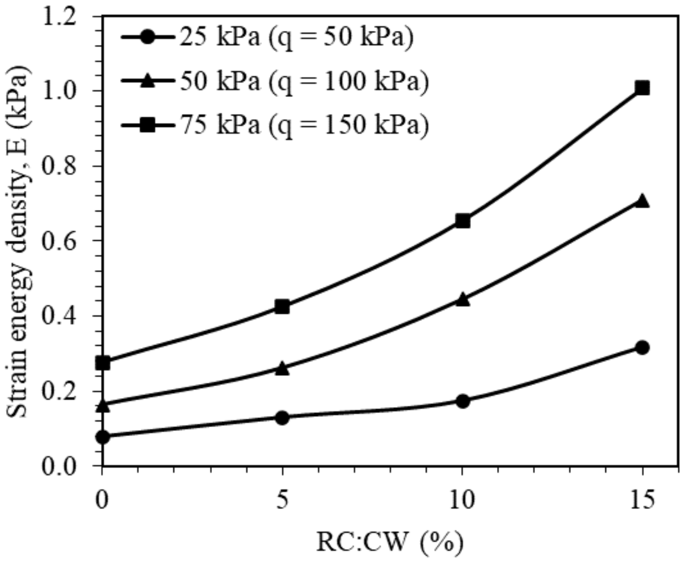
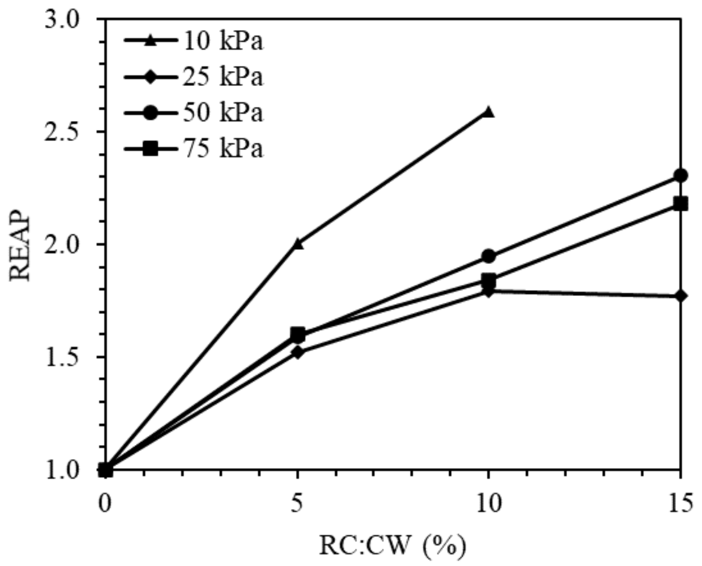


Figure 9. Strain energy density of CW-RC mixtures at a stress ratio of $q = 2\sigma'_3$ typically experienced at the subballast layer



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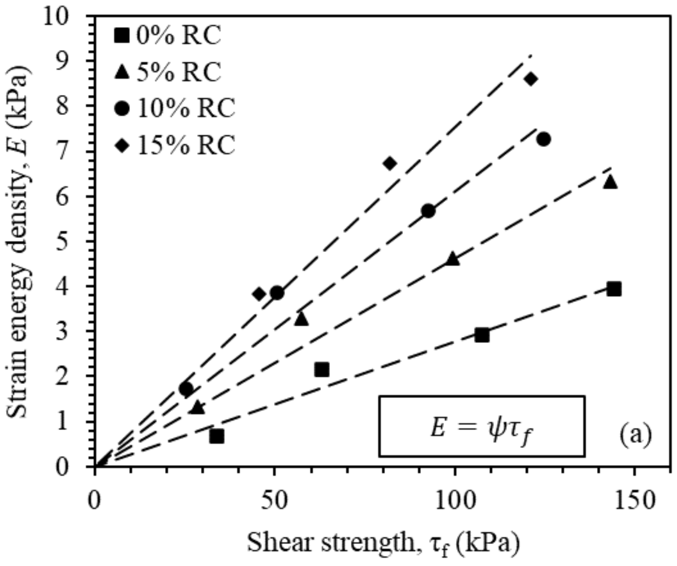

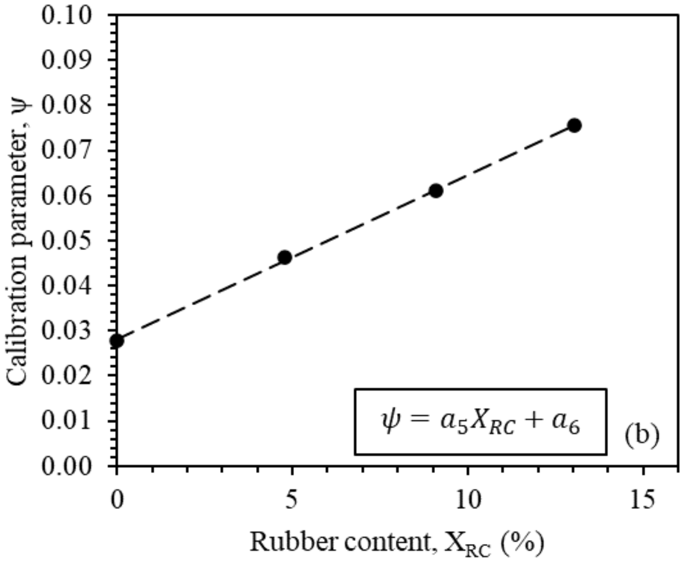

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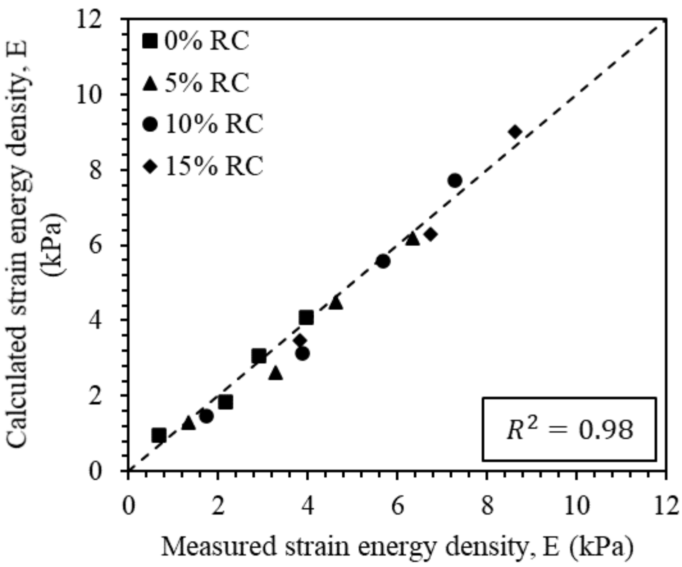

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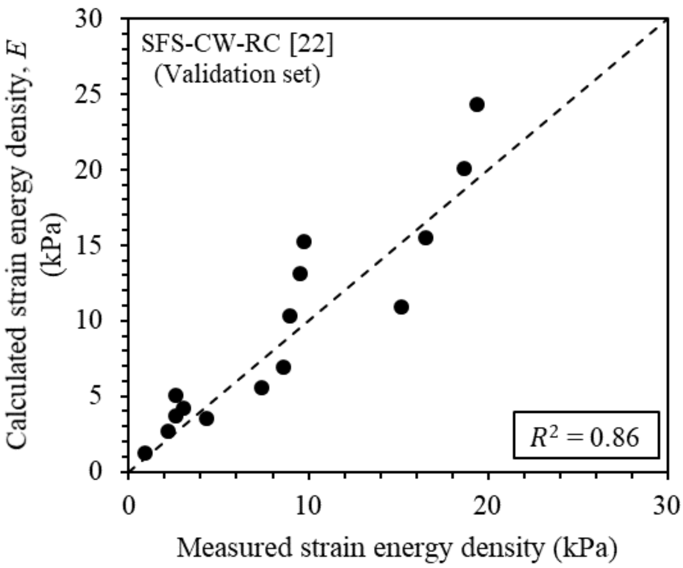

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